Optimization of Knitted Fabric Comfort and UV Protection using Desirability Function

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ABSTRACT

The present study deals with the optimization of multiple quality parameters of single jersey and 1×1 rib knitted fabrics using the desirability function approach. Comfort properties such as air permeability, thermal conductivity and safety properties such as UV protection are combined to yield an 'overall desirability' varying from zero to one. The overall desirability has been maximized versus target values for air permeability, thermal conductivity and UV resistance. Experimental validation confirms that the proposed method can be used to design a knitted fabric with desired comfort and UV resistance characteristics.

INTRODUCTION

A porous structure is found to be more comfortable due to high breathability and permeability. Hence, knitted fabrics with porous structures have become popular as summer wear [1]. However, the heat generated by physical activity is dissipated to the atmosphere through the respiratory system and skin. Thus, in a cold climate a textile would be comfortable if it does not allow body heat to dissipate whereas in hot climatic condition, transmission of body heat is desirable. In hot climates, open fabric enhances air permeability, resulting in more heat loss through convection. Further, the open structure of a fabric reduces heat transmission through conduction. However, porous structures expose the skin to dangerous UV rays. Though a certain degree of UV exposure is required for vitamin D synthesis in human body, over exposure can result in erythema, sun-tanning, skin-cancer, etc. [2-6]. The UV resistance of textile clothing is expressed by UPF (ultraviolet protection factor), which rates the extent of sunburn protection provided by the textile. Textiles are classified as 'good protection' (UPF range 15 to 24), 'very good protection' (UPF range 25 to 39), and 'excellent protection' (UPF more than 40) based on their UPF values [7, 8].

Researchers have studied various parameters affecting the comfort and UV resistance of textiles. It was inferred from various studies that the UPF of textiles depends on type of fiber, type of yarn, cover factor / tightness factor of a fabric, areal density, finishing etc. [9-14]. In contrast the comfort properties of knitted fabrics depend on such factors as air permeability, thermal conductivity, moisture management etc. depend on type of fiber, yarn structure, fabric structure i.e. porosity [15-18].

Consequently, optimization of fabric properties such as air permeability, thermal conductivity and UV resistance are basically will require adjustment of several conflicting parameters. Higher air permeability results in low thermal conductivity as well as low UPF and vice-versa. For example, cotton knitted fabrics designed for summer wear will require a balance between two conflicting parameters, air permeability and thermal conductivity for optimum comfort. Nevertheless, the UPF of the fabric should have a desired level that decides the protection from harmful UV rays. Hence, to achieve a fabric with optimum comfort as well as desired UV protection, it is necessary to optimize multiple parameters simultaneously.

Harrington [19] developed the concept of desirability function in 1965 and it was further developed by Derringer and Suich [20]. Taieb et al. [21] used desirability function to optimize knitted fabric quality, which comprises various mechanical properties such as areal density, bursting pressure, extensibility, dimensional stability, abrasion resistance etc. Souid et al. [22] estimated denim fabric quality using desirability function. Asim et al. [23] optimized the process parameters for simultaneous fixation of reactive printing and crease resistant finishing using desirability function. However, no study in the literature addresses the simultaneous optimization of comfort and UV resistance for textile fabrics.

In this experimental work the desirability function technique is used to determine the values of the controlled factors that yield the 'maximum desirable' values of fabric response parameters including air permeability, thermal conductivity and UPF, for both single jersey and 1×1 rib knitted fabrics.

MATERIALS AND METHODS

Materials

Yarns spun with one hundred percent cotton fibers were used to prepare single jersey and 1×1 rib knitted fabric samples by choosing four factors: loop length (X_1), carriage speed (X_2), yarn input tension (X_3) and yarn count (X_4) each at three different levels. The coded level and the actual level of the factors are shown in *Table I*.

TABLE I. Actual values of the factors corresponding to their coded levels.

	Coded level	Variables			
		Loop length	Carriage speed	Yarn input tension	Yarn count
		(X_1)	(X_2)	(X_3)	(X_4)
		mm	m/s	gf	Ne
Single jersey	-1	6.6	0.25	6	5
	0	7	0.6	8	7.5
	1	7.4	0.95	10	10
1×1 rib	-1	5.09	0.25	6	5
	0	5.39	0.45	8	7.5
	1	5.69	0.65	10	10

A total of thirty six single jersey and thirty six 1×1 rib knitted fabric samples were prepared in a 12 gauge computerized flat knitting machine as the per 4-factor-3-level orthogonal block Box and Behnken experimental design [24] illustrated below.

$$\begin{bmatrix} \pm1 & \pm1 & \pm & 0 \\ \pm1 & \pm1 & 0 & \pm1 \\ \pm1 & 0 & \pm1 & \pm1 \\ 0 & \pm1 & \pm1 & \pm1 \end{bmatrix}$$

Testing

All the seventy two knitted fabric samples were washed in a Washcator washing machine for complete relaxation per EN ISO 6330 [25]. The samples were then conditioned at standard atmospheric conditions for 48 hours. The samples were subsequently evaluated for air permeability, thermal conductivity and UPF. For each sample, 10 readings were taken for air permeability, thermal conductivity and UPF and their average values were determined.

Air permeability testing was conducted using a TEXTTEST FX3300 air permeability tester per ASTM D737 [26]. A pressure gradient of 100 Pa was maintained across the fabric samples during the test.

Thermal conductivity testing was conducted using an Alambeta instrument per ISO EN 31092 [27]. The measuring head temperature and contact pressure were maintained at 32ºC and 200 Pa respectively.

UPF testing was conducted using a Labsphere 2000F and was determined by the in-vitro method per AATCC 183:2004 [28]. The UPF of a fabric sample was calculated using the following equation.

$$UPF = \frac{\sum_{290}^{400} E(\lambda)S(\lambda)\Delta(\lambda)}{\sum_{290}^{400} E(\lambda)S(\lambda)\mathrm{T}(\lambda)\Delta(\lambda)} \quad (1)$$

Where *E(λ)* is the relative erythemal spectral effectiveness, *S(λ)* is the solar spectral irradiance [W/m^{2}nm], *Δλ* is the measured wavelength interval [nm] and *T(λ)* =is the average spectral transmittance of the sample.

Response Surface Equations

A quadratic regression equation model used to relate various independent factors including loop length, carriage speed, yarn input tension, yarn count with air permeability, thermal conductivity and UPF. Eq. (2) shows the general form of the model:

$$\begin{aligned} Y = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 + \alpha_4 X_4 \\ + \alpha_5 X_1 X_2 + \alpha_6 X_1 X_3 \\ + \alpha_7 X_1 X_4 + \alpha_8 X_2 X_3 \\ + \alpha_9 X_2 X_4 + \alpha_{10} X_3 X_4 \\ + \alpha_{11} X_1^2 + \alpha_{12} X_2^2 \\ + \alpha_{13} X_3^2 + \alpha_{14} X_4^2 \end{aligned} \quad (2)$$

Where, Y is the dependent variable, X_1, X_2, X_3 and X_4 are the inputs to the model and α_0, α_1, α_2, α_3, ... α_{14} are the regression coefficients. In the fitted regression equations only the regression coefficients which are significant at 95% confidence limits are considered.

Desirability Function

A desirability function (d_i) is defined individually for each response parameter including targets and boundaries. The desirability functions with different targets and boundaries are shown in *Figure 1*. There are three types of targets: maximum response, minimum response and target response. Equations defining each type of response are expressed in *Table II*.

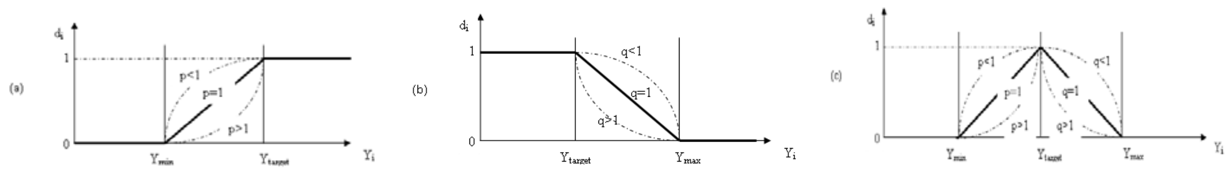

FIGURE 1. Desirablity function to (a) maximize; (b) minimize; (c) reach a target value

The exponents' p and q in the *Table II* determine the degree of importance of hitting target value. The desirability function approaches linear for $p = q = 1$. The desirability function is convex for $p < 1$, $q < 1$ and is concave for $p > 1$, $q > 1$.

The d_i values are combined to calculate the 'overall desirability function' for optimization. The equation of 'overall desirability function' is manifested in the following equation:

$$D = \sqrt[w]{\left(d_1^{w_1} \times d_2^{w_2} \times \ldots . \times d_n^{w_n}\right)} \qquad (3)$$

Where $w = \sum w_i$, w_i is the weight of i^{th} response and n is the number of responses. Both the 'individual desirability function' and 'overall desirability function' have a range from 'zero' to 'one'. A desirability of 'zero' corresponds to a completely undesirable property whereas a value of 'one' indicates an ideal response value.

TABLE II. Expressions of desirability functions for different target values.

Maximize the response	Minimize the response	Target the response
$d_i = \left(\frac{Y_i - Y_{\min}}{Y_{\text{target}} - Y_{\min}}\right)^p$	$d_i = \left(\frac{Y_i - Y_{\max}}{Y_{\text{target}} - Y_{\max}}\right)^q$	$d_i = \left(\frac{Y_i - Y_{\min}}{Y_{\text{target}} - Y_{\min}}\right)^p$
where $Y_{\min} \le Y_i \le Y_{\text{target}}$	where $Y_{\text{target}} \le Y_i \le Y_{\max}$	where $Y_{\min} \le Y_i \le Y_{\text{target}}$
$d_i = 0$, if $Y_i \le Y_{\min}$ $d_i = 1$, if $Y_i \ge Y_{\text{target}}$	$d_i = 0$, if $Y_i \ge Y_{\max}$ $d_i = 1$, if $Y_i \le Y_{\text{target}}$	$d_i = 0$, if $Y_i \le Y_{\min}$ $d_i = 1$, if $Y_i = Y_{\text{target}}$
		and
		$d_i = \left(\frac{Y_i - Y_{max}}{Y_{target} - Y_{max}}\right)^q$
		where $Y_{\text{target}} \le Y_i \le Y_{\max}$
		$d_i = 0$, if $Y_i \ge Y_{\max}$ $d_i = 1$, if $Y_i = Y_{\text{target}}$

RESULTS AND DISCUSSION

A quadratic regression model was used to relate the loop length, yarn input tension, and carriage speed and yarn count to the air permeability, thermal conductivity, and UPF for both types of fabrics. The general form of the quadratic regression model is shown in Eq. (2). Significant tests were conducted on regression coefficients of the quadratic regression models. The regression coefficients, t statistics and p-values of all the terms for single jersey and 1×1 rib knitted fabrics are shown in *Table III* and *Table IV* respectively. The regression coefficients, which are significant at 95% confidence level, were considered for further investigations. The regression coefficients with p-values less than 0.05 are statistically significant at a 95% confidence level. The response surface equations for air permeability, thermal conductivity and UPF and their corresponding coefficients of determination (R^2) for both single jersey and 1×1 rib fabrics are shown in *Table V* [29, 30].

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TABLE III. Regression statistics coefficients for different response variables using coded values of the input variables for single jersey fabric.

Term	Air permeability			Thermal conductivity			UPF		
	Coefficient	t-Stat	p-value	Coefficient	t-Stat	p-value	Coefficient	t-Stat	p-value
Constant	134.25	26.16	$1.64{\times}10^{-17}$*	38.85	82.82	$6.67{\times}10^{-28}$*	10.05	18.9	$1.16{\times}10^{-14}$*
X_1	22.29	10.64	$6.48{\times}10^{-10}$*	-0.78	-4.09	0.0005*	-1.69	-7.77	$1.32{\times}10^{-7}$*
X_2	2.21	1.06	0.303	-0.01	-0.07	0.9486	0.19	0.88	0.3885
X_3	-0.66	-0.32	0.754	-0.19	-1	0.3283	0.16	0.74	0.4694
X_4	111.49	53.22	$6.85{\times}10^{-24}$*	-4.6	-24	$9.34{\times}10^{-17}$*	-7.69	-35.4	$3.29{\times}10^{-20}$*
X_1X_2	1.75	0.68	0.503	-0.43	-1.81	0.0843	-0.25	0.94	0.3579
X_1X_3	-0.11	-0.04	0.967	0.04	0.19	0.8538	-0.3	-1.14	0.2672
X_1X_4	9.6	3.74	0.001*	-0.06	-0.24	0.8128	1.32	4.95	$6.72{\times}10^{-5}$*
X_2X_3	2.51	0.98	0.339	-0.21	-0.91	0.3752	-0.44	-1.65	0.1139
X_2X_4	3.84	1.5	0.15	0.41	1.76	0.0932	-0.32	-1.21	0.2405
X_3X_4	-0.61	-0.24	0.815	0.08	0.35	0.7325	-0.37	-1.39	0.1794
X_1^2	-0.81	-0.22	0.826	-0.44	-1.33	0.1973	-0.24	-0.64	0.5317
X_2^2	-4.57	-1.26	0.222	0.12	0.36	0.7193	0.69	1.83	0.081
X_3^2	10.36	2.86	0.009*	-0.22	-0.65	0.5207	-0.49	-1.31	0.2063
X_4^2	25.94	7.15	$4.76{\times}10^{-7}$*	1.16	3.49	0.0022*	2.05	5.45	$2.11{\times}10^{-5}$*

*Statistically significant 95% confidence level

TABLE IV. Regression statistics for different response variables using coded values of the input variables for 1×1 rib fabric.

Term	Air permeability			Thermal conductivity			UPF		
	Coefficient	t-Stat	p-value	Coefficient	t-Stat	p-value	Coefficient	t-Stat	p-value
Constant	48.93	32.83	$1.56{\times}10^{-19}$*	52.83	66.61	$6.36{\times}10^{-26}$*	59.97	11.56	$1.44{\times}10^{-10}$*
X_1	13.05	21.45	$9.21{\times}10^{-16}$*	-3.7	-11.4	$1.82{\times}10^{-10}$*	-19.45	-9.19	$8.37{\times}10^{-9}$*
X_2	-0.34	-0.56	0.5836	-0.05	-0.14	0.8888	-0.23	-0.11	0.9155
X_3	-0.83	-1.37	0.1855	0.13	0.41	0.6846	1.29	0.61	0.55
X_4	42.33	69.57	$2.57{\times}10^{-26}$*	-10.18	-31.5	$3.77{\times}10^{-19}$*	-53.97	-25.5	$2.94{\times}10^{-17}$*
X_1X_2	-0.85	-1.14	0.2686	-0.21	-0.54	0.5976	2.92	1.12	0.2733
X_1X_3	-0.38	-0.5	0.6195	0.19	0.49	0.6302	-1.74	-0.67	0.5086
X_1X_4	6.26	8.4	$3.71{\times}10^{-8}$*	0.79	2	0.0584	17.42	6.72	$1.19{\times}10^{-6}$*
X_2X_3	-1.29	-1.73	0.098	-0.26	-0.65	0.5251	1.65	0.64	0.5305
X_2X_4	-0.12	-0.15	0.8788	0.6	1.53	0.1412	0.91	0.35	0.729
X_3X_4	-0.36	-0.49	0.6317	-0.38	-0.95	0.355	-1.27	-0.49	0.63
X_1^2	0.55	0.53	0.6042	-0.31	0.56	0.5832	6.09	1.66	0.1115
X_2^2	0.31	0.3	0.77	-0.49	-0.87	0.3945	-1.75	-0.48	0.6389
X_3^2	0.55	0.52	0.6075	-0.18	-0.31	0.7581	-0.59	-0.16	0.8733
X_4^2	12.28	11.65	$1.26{\times}10^{-10}$*	2.22	3.97	0.0007*	19.97	5.44	$2.11{\times}10^{-5}$*

*Statistically significant 95% confidence level

TABLE V. Response surface equations of various parameters.

Type of fabrics	Response variables		
	Air permeability	Thermal conductivity	UPF
Single-jersey	$134.25 + 22.29X_1 + 111.49X_4 + 9.60X_1X_4 + 10.36X_3^2 + 25.94X_4^2$	$38.85 - 0.78X_{-1} - 4.60X_4 + 1.16X_4^2$	$10.05 - 1.69X_1 - 7.69X_4 + 1.32X_1X_4 + 2.05X_4^2$
	($R^2 = 0.99$)	($R^2 = 0.95$)	($R^2 = 0.97$)
1×1 rib	$48.93 + 13.05X_1 + 42.33X_4 + 6.26X_1X_4 + 12.28X_4^2$	$52.83 - 3.70X_{-1} - 10.18X_4 + 2.22X_4^2$	$59.97 - 19.45X_1 - 53.97X_4 + 17.42X_1X_4 + 19.97X_4^2$
	($R^2 = 0.99$)	($R^2 = 0.97$)	($R^2 = 0.97$)

It is apparent from the equations that, while the yarn count and loop length are the key factors affecting the air permeability, thermal conductivity and UPF, the carriage speed has no significant effect on these response variables in the case of both the single jersey and 1×1 rib knitted fabrics. However, the yarn input tension has little effect on the air permeability of the single jersey fabric and hence it is removed from the response surface equation. The response surface equation the air permeability of single jersey fabric was thus rewritten as:

$$\text{Air permeability} = 134.25 + 22.29X_1 + 111.49X_4 + 9.60X_1X_4 + 25.94X_4^2 \quad (4)$$

In the present work, the objective is to achieve the target values for air permeability, thermal conductivity and UPF for both the single jersey and 1×1 rib knitted fabrics by optimizing the 'overall-desirability'. The target values were set using data collected from literature and experience. The minimum and maximum values for air permeability, thermal conductivity and UPF were estimated from their corresponding response surface equations.

Table VI shows the target, minimum and maximum values for air permeability, thermal conductivity and UPF for both types of fabrics. To find the 'individual desirability' for each property, target response equations shown in the last column of *Table II* were used. In this study, the values of p and q were chosen as 1. The diagrams of the 'individual desirability' of each property of single jersey and 1×1 rib fabrics are depicted in *Figure 2* and *Figure 3* respectively. The 'overall desirability' as expressed in Eq. (3) was determined for each type of fabric using MATLAB Optimization Toolbox (version 7.7) to solve the equation for maximum values. The weight value (w_i) was chosen as 1 which implies equal importance among responses.

TABLE VI. The boundaries and target values of different responses.

Fabric type	Responses	Lower limit	Target	Upper limit
Single jersey	Air permeability ($cm^3/cm^2/s$)	36.01	80	303.57
	Thermal conductivity ($W/mK\times10^{-3}$)	34.63	40	45.39
	UPF	4.04	15	22.8
1×1 rib	Air permeability ($cm^3/cm^2/s$)	12.09	80	122.85
	Thermal conductivity (W/mK×10-3)	41.17	40	68.93
	UPF	23.94	25	170.78

The solutions resulting from this optimization exercise are given in *Table VII*. In case of single jersey, the maximum 'overall desirability' value is estimated as 0.91 which corresponds the optimum values of 80.6, 41.3 and 15 for air permeability, thermal conductivity and UPF respectively at 6.6 mm loop length and 6.7 Ne yarn count. In the case of 1×1 rib fabric, the optimum values of air permeability, thermal conductivity and UPF are obtained as 80, 45.9 and 30.4 respectively, which yield a maximum 'overall desirability' value of 0.92 at 5.69 mm loop length and 8.4 Ne yarn count. The overall-desirability curve for single jersey and 1×1 rib knitted fabrics are shown in *Figure 4* and *Figure 5* respectively. It is also evident from *Table VII* that single jersey fabric and 1×1 rib knitted fabric ensure 'good protection' and 'very good protection' respectively from the UV rays, with desired values of air permeability and thermal conductivity. Moreover, for a given machine gauge and yarn count, 1×1 rib fabric provides slightly better comfort with more UV protection than single jersey fabric.

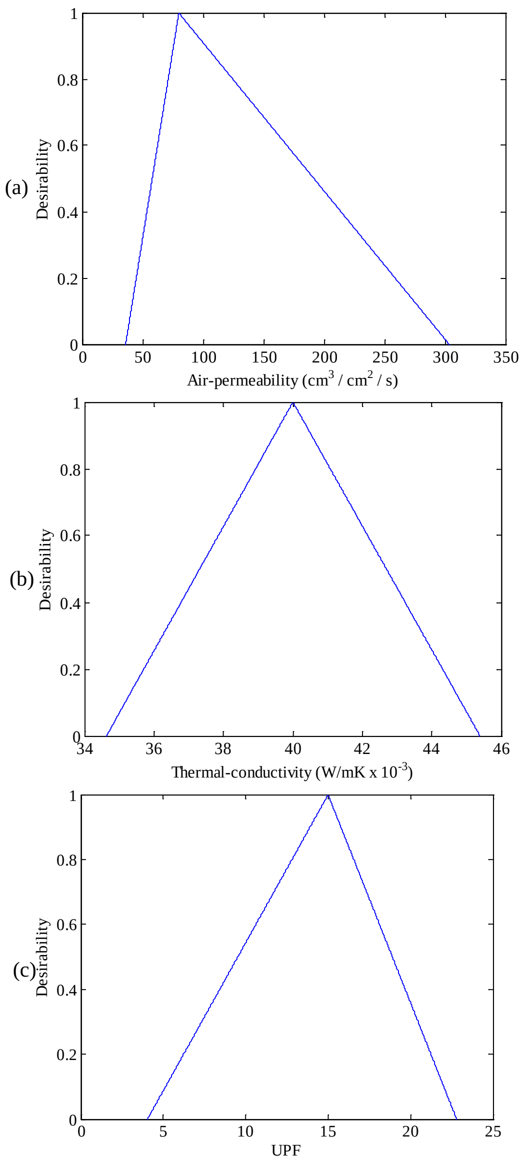

FIGURE 2. Individual desirability function diagram of (a) air permeability, (b) thermal conductivity and (c) UPF for single jersey fabric.

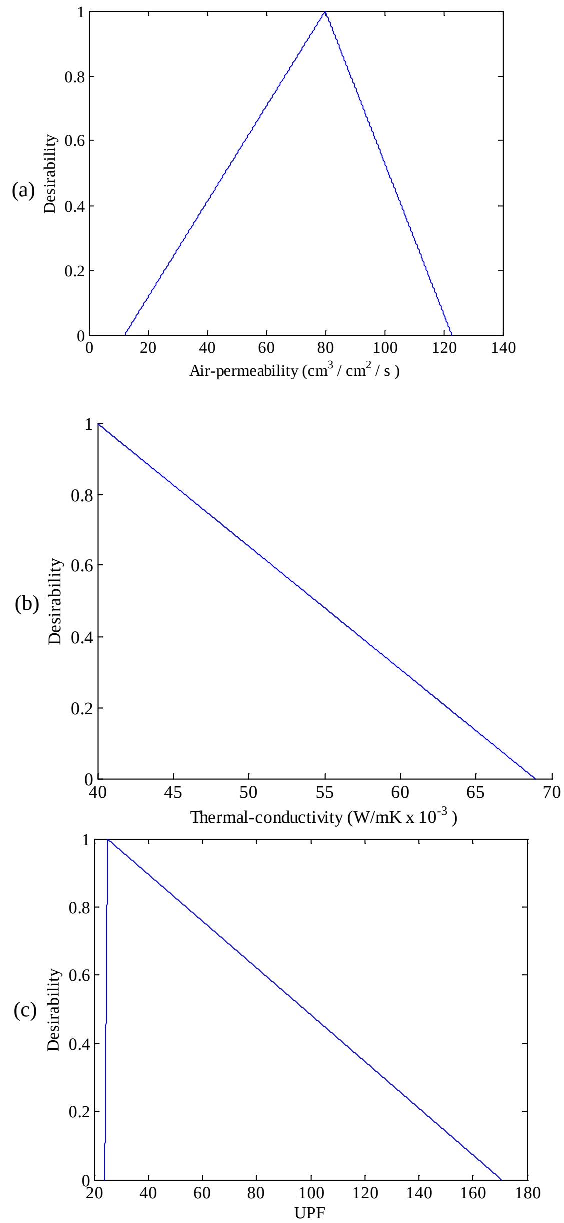

FIGURE 3. Individual desirability function diagram of (a) air permeability, (b) thermal conductivity and (c) UPF for 1×1 rib fabric.

TABLE VII. Solutions of optimization problems for single jersey and 1×1 rib fabrics.

Fabric type	Responses	Predicted value of the response	Overall desirability value	Solution
Single jersey	Air permeability ($cm^3/cm^2/s$)	80.6	0.91	X_1 = 6.6 mm X4 = 6.7 Ne
	Thermal conductivity ($W/mK\times10^{-3}$)	41.3		
	UPF	15		
1×1 rib	Air permeability ($cm^3/cm^2/s$)	80	0.92	X_1 = 5.69 mm X4 = 8.4 Ne
	Thermal conductivity (W/mK×10-3)	45.9		
	UPF	30.4		

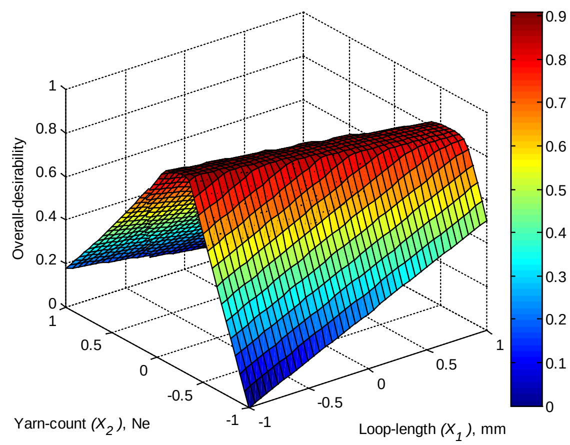

FIGURE 4. Overall-desirability as a function of yarn count and loop length for single jersey fabric.

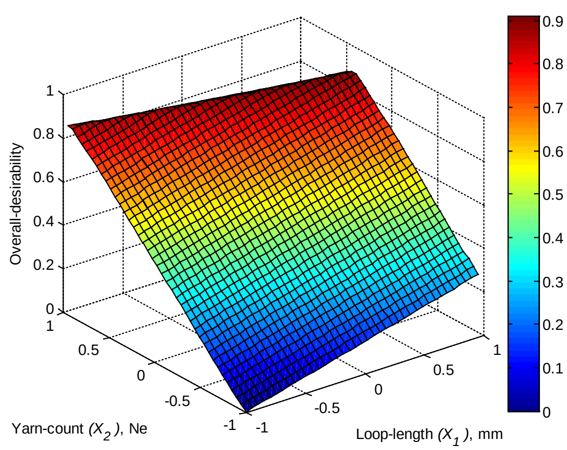

FIGURE 5. Overall-desirability as a function of yarn count and loop length for 1×1 rib fabric.

EXPERIMENTAL VALIDATION

The optimization model was validated by comparing optimum values and actual results. For this purpose, single jersey and 1×1 rib knitted fabric samples were made in the same 12 gauge computerized flat knitting machine equipped with 'digital loop control system' to acquire the desired loop length. One hundred percent cotton yarns of 6.5 Ne (≈ 6.7 Ne) and 8.5 Ne (≈ 8.4 Ne) were used to manufacture single jersey and 1×1 rib knitted fabrics respectively. The loop length for single jersey and 1×1 rib were chosen as 6.6 mm and 5.69 mm respectively. The samples were completely relaxed by washing, conditioned and tested for air permeability, thermal conductivity and UPF per the standards listed previously. *Table VIII* shows the actual and calculated optimum values of air permeability, thermal conductivity and UPF for both single jersey and 1×1 rib knitted fabrics. It is evident from the *Table VIII* that the actual values of air permeability, thermal conductivity and UPF are very close to the calculated optimum values with an error of less than 5% in all cases for both the single jersey and 1×1 rib knitted fabrics.

TABLE VIII. Optimized and achieved fabric properties.

Fabric type	Air permeability ($cm^3/cm^2/s$)			Thermal conductivity ($W/mK\times10^{-3}$)			UPF		
	O	A	Error %	O	A	Error %	O	A	Error %
Single-jersey	80.6	83.4	3.40%	41.3	40.1	3.00%	15	15.3	1.96%
1×1 rib	80	82.9	3.50%	45.9	43.8	4.80%	30.4	29.1	4.50%

O = Optimized value, A= Achieved value

CONCLUSION

In this study an adaptive method was used to combine optimize key properties of knitted fabrics and yield to a single 'overall desirability' index which varies from 0 to 1. The overall desirability index was maximized by optimizing multiple properties such as air permeability, thermal conductivity and UV resistance against target values. Optimum values are obtained for loop length and yarn count in order to maximize the "overall desirability" and engineer a knitted fabric with desired combinations of comfort and UV resistance. The experimental results show significant agreement between the actual and calculated values of the key fabric properties. This study may lead to the development of a single point grade scale from 0 to 1 which can be used to rank knitted fabrics for target comfort and UV resistant properties.

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